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SU-SEL-68-045

AD834360

Lateral Deviation of Obliquely Propagated HF Radio Rays

by

T. W. Washburn

MAY 1968

Technical Report No. 137

Prepared under
Office of Naval Research Contract
Nonr-225(64), NR 088 019, and
Advanced Research Projects Agency ARPA Order 196

RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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ABSTRACT

As is well known, magnetoionic splitting of obliquely propagated HF radio waves may result in deviation of such waves from the great-circle plane between transmitter and receiver. A computer raytracing routine has been employed at Stanford to investigate the properties and maximum extent of this phenomenon under realistic ionospheric conditions. It is concluded that for a 1000 km path the difference in azimuthal bearing between the ordinary and extraordinary modes could reach a maximum of 0.5 deg, corresponding to an 0.25 deg variation of either mode from the true bearing. However, in most practical bearing estimation problems, the difference is an order of magnitude smaller than this maximum, and thus is truly small in comparison with other sources of error.

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ILLUSTRATIONS

I. INTRODUCTION

It is well known that interaction with the earth's magnetic field may cause obliquely propagated HF radio rays to deviate from the great-circle path determined by the initial direction of the ray. Under certain ionospheric conditions an obliquely propagated ray may return to earth in a great-circle plane different from, but parallel to, the initial great-circle plane. This phenomenon can be a source of error in determining the azimuthal bearing from a point of observation to the source of a ray, as in a direction-finding system. A number of investigators have studied this problem with varying degrees of success; most of the limitations on their findings have arisen by virtue of extensive approximations necessary to make the problem amenable to manual computation.

In this report the results of a study of the possible import of lateral deviation caused by the earth's magnetic field will be described. A fairly sophisticated raytracing technique has been used in a high-speed digital computation routine. It should be pointed out that this study represents only a brief inquiry into the properties and extent of lateral deviation. A particular goal was to obtain a working estimate of the maximum value of deviation obtained in realistic propagation situations. For this reason, the results depicted herein are only representative examples of lateral deviation, rather than an exhaustive study of the phenomenon.

Perhaps it is best to begin by summarizing some of the earlier work, which by and large gives a good account of the qualitative aspects of the problem, but a somewhat inconsistent picture of the maximum magnitude of bearing errors which one may expect.

Booker (1949)[†] employed his famous quartic formulation to obtain an analytical expression for the differential lateral displacement of a radio ray. This expression, when integrated over the ray path, could yield a value for the net lateral deviation of the ray. However, Booker did not perform any calculations for this net effect, and observed only that its magnitude would be small except in unusual circumstances. Elghozi (1953) reviewed the work of Al'pert (1948) and extended Booker's analysis to determine the extent of lateral deviation over some specific paths (mostly near-vertical). Millington (1951, 1954) reduced the quartic equation to a quadratic equation under a number of assumptions and looked at the limiting value of lateral deviation as the ray moved toward vertical incidence. His notation is difficult to follow, but Gething (1962) reformulated Millington's work into a more conventional format and extended the calculations somewhat to arrive at an estimate of the maximum bearing error that is possible because of lateral deviation in a parabolic ionospheric layer. Titheridge (1959) employed many approximations to enable him to calculate lateral deviation in a linear or parabolic layer. His parameterization of the problem is somewhat ambiguous, and his results do not compare in a reliable manner with those described in this report. Furthermore, he compared his results with those of Chatterjee (1952) and drew attention to good agreement between the two sets of results; yet his choice of layer critical frequency was significantly different from the choice Chatterjee made for the purpose of his calculation.

[†] All references are listed alphabetically in the Bibliography at the end of the paper.

Several other investigators have considered the lateral deviation problem, particularly for vertical incidence [see Kelso (1964) and NBS Monograph 80 for a review for this work]. A summary of the various aspects of direction finding may be found in the recent review article by Gething (1966). Without embarking upon a critical review of the generous supply of previous work on this subject, it is important to observe that all of the previous work assumed a single linear or parabolic ionospheric layer for ease of computation. Use of a more realistic ionospheric profile should give one greater confidence in the results obtained. Furthermore, in the previous work values were used for several ionospheric parameters, which are not found in practice; yet no attempts were made to verify that the use of such values does not alter the results significantly.

As an example, Gething (1962) computes the maximum bearing error over a path where $Y = 1/2$, which corresponds to signal frequencies in the vicinity of 2 MHz. Near the gyro frequency the rays have stronger magnetic interaction and will display relatively large deviation. Gething quotes a maximum bearing error of 6.8 deg for the ordinary mode and 4.1 deg for the extraordinary mode in a parabolic ionospheric layer; however, this condition occurs where the ratio of plasma frequency at the path apex to plasma frequency at the layer maximum tends very closely to one (0.98 and higher). In practice, very little energy ever gets this deep within the ionosphere without penetrating the entire layer. Reference to Fig. 1 in Gething's paper will show that revising the maximum attained value of the ratio downward to 0.97 will reduce his estimate of maximum bearing errors by a factor of three. One may also note that in Gething's

figure, the ratio mentioned above is incorrectly interpreted as the ratio of signal frequency to maximum usable frequency (MUF). This incorrect interpretation was first pointed out to the author by Dr. J. M. Kelso of the ITT Electro-Physics Laboratories. Finally, one should emphasize that Gething's computations were made for a range of about 600 km. As will be pointed out later, range is a major factor in determining angular bearing errors.

II. COMPUTATION OF LATERAL DEVIATION

In 1963, Finney programmed a solution of the Haselgrove equations [Haselgrove (1954)] to trace rays through an ionosphere of arbitrary vertical electron density profile while employing a dipole model of the earth's magnetic field. Dr. T. A. Croft of the Radioscience Laboratory at Stanford University has implemented Finney's work for use at the university. A number of ionospheric ray paths have been computed by means of the resulting program, and by varying the parameters involved, a fairly good description of the qualitative features of lateral deviation may be constructed. In accordance with the primary purpose of the present study, an estimate of the magnitude of the lateral deviation effect is obtained under various ionospheric conditions. This technique appears to provide a quick and inexpensive way to obtain the bearing error over types of oblique paths found in practice. In the summary of the technique that follows, it becomes readily apparent that a qualitative description of the features of the phenomenon of lateral deviation is complex, since the effects of the several ionospheric parameters involved are highly interdependent.

A convex electron density profile with a critical frequency of 9 MHz (see Fig. 1) was employed for most of the computation. Such a density profile is fairly representative of daytime ambient conditions.

The magnetic azimuth ϕ_M, defined as the clockwise angle from the vertical plane that passes through the magnetic field lines to the vertical plane that passes through the initial ray direction, is an important parameter. For $\phi_M = 0$ deg or 180 deg the raypath remains in the great-circle path between take-off and landing points. For $\phi_M = 90$ deg or

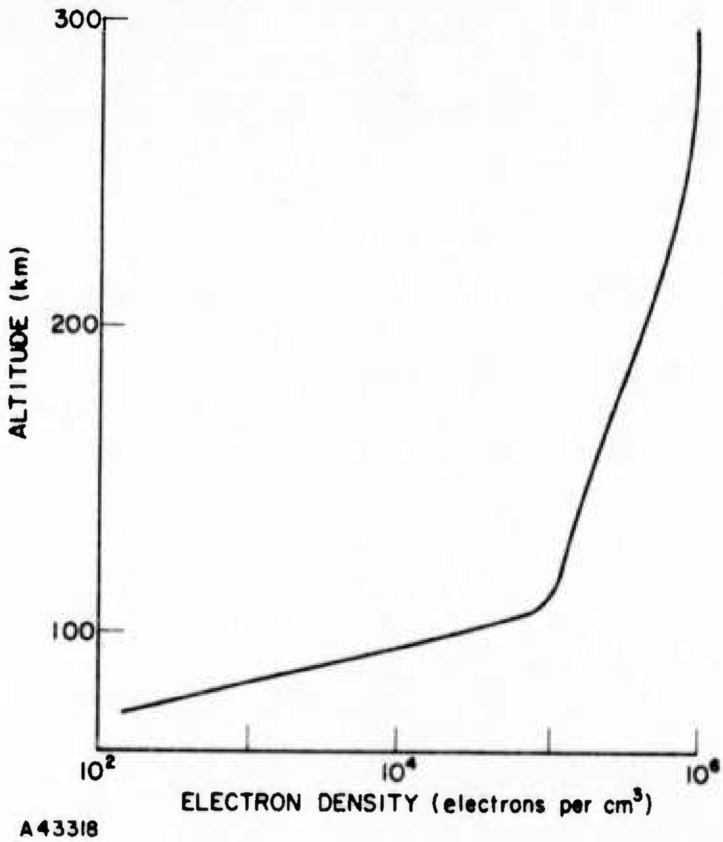

FIG. 1. ELECTRON DENSITY PROFILE USED IN COMPUTATION OF LATERAL DEVIATION. Critical frequency, 9 MHz.

270 deg the ray path may be diverted from the great-circle path while the ray is in the ionosphere; but it always returns to the great-circle path upon returning to earth. These properties were observed analytically by Booker (1949); and the computations performed by the author of the present study, using the Finney raytracing routine, bear out the predictions. If the magnetic azimuth for an oblique path lies between the two extremes, a net lateral deviation with attendant bearing error may arise.

Figure 2a depicts an example of a ray path that exhibits net lateral deviation upon returning to earth. The observation that the ray comes to earth in a plane parallel to, but not necessarily coincident with,

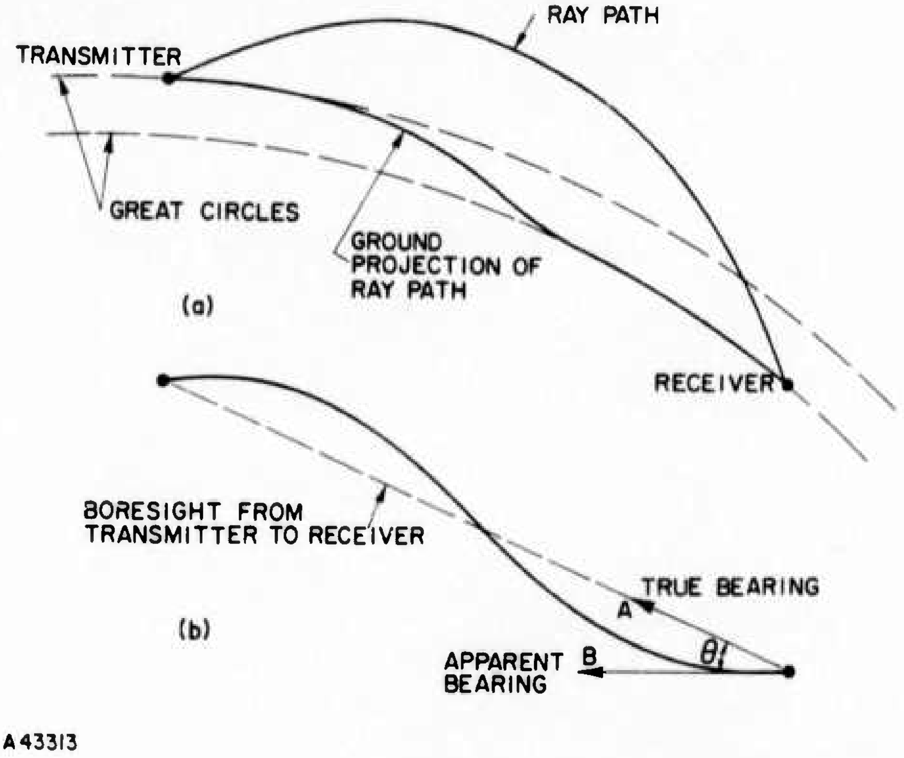

FIG. 2. EXAMPLE OF A RAY PATH EXHIBITING NET LATERAL DEVIATION.

a. Profile of ray path

b. Ground projection of ray path

its plane of departure has been confirmed analytically by Budden (1961) directly from the Booker formulation. The condition comes about because the ray direction departs from the plane of incidence while in the ionosphere, although the wave normal remains in the plane of incidence at all times. Figure 2b shows the ground projection of the ray path. The ground projection contains the pertinent information for azimuthal bearing determination. Direction A is the true bearing to the transmitter, while direction B indicates the apparent bearing. The angle of error in bearing is θ.

Figure 3a depicts an example of the ground projection of the ordinary and extraordinary rays in a ray path with lateral deviation. The angle

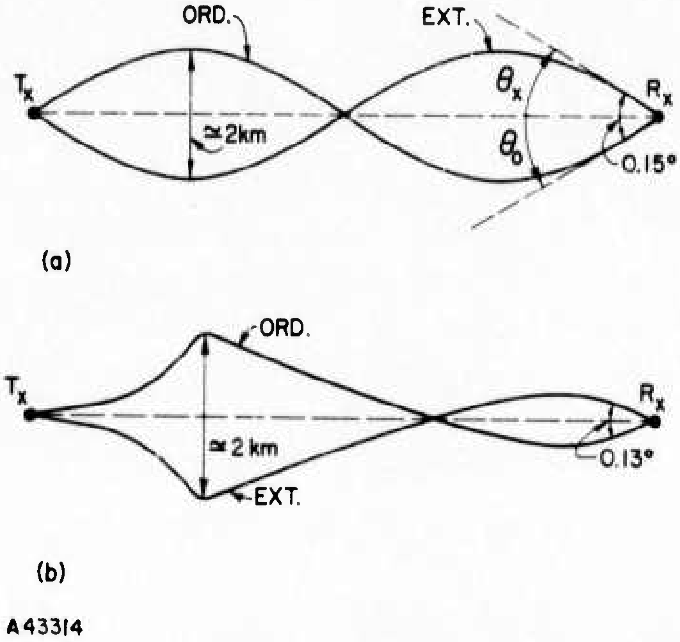

FIG. 3. REPRESENTATIVE GROUND PROJECTIONS OF ORDINARY AND EXTRAORDINARY RAY PATHS EXHIBITING NET LATERAL DEVIATION.

a. $\phi_M = 30°$, $\beta = 32°$, $f = 10$ MHz, $R = 1000$ km

b. $\phi_M = 54°$, $\beta = 27°$, $f = 12$ MHz, $R = 1022$ km

θ_o is the angular bearing error for the ordinary ray, and θ_x for the extraordinary ray. A convenient measure of bearing errors is $\Delta\theta$, which is the angular magnitude of the difference between θ_o and θ_x; this measure is useful because the ray paths for the two modes are usually much like mirror images of each other; therefore

$$|\theta_o - \theta_{true}| \simeq \frac{1}{2}\Delta\theta ,$$

and similarly for θ_x. As is well known (see NBS monograph 80), the point of reflection for the ordinary ray is deflected toward the nearer pole, while the extraordinary ray is deflected toward the equator. If used carefully, this observation serves as a guide for outlining qualitative features of the ray path behavior.

Under some conditions, the loci of the ground projections of the ray paths are more distorted than in Fig. 3a, as is indicated in Fig. 3b; however, the essential features of the situation do not change much.

One comment is in order here--namely, that the deviated rays are near the great-circle path in the region of the path midpoint, except for the case of propagation transverse to the field lines. This means, contrary to the conclusions drawn by some observers, that the deviated ray does not sample a significantly different part of the ionosphere than does an undeviated ray, particularly near the path apex, where ionospheric variability is large and tends to have maximum effect upon ray path parameters.

Figure 4 shows the variation of bearing error $\Delta\theta$ vs magnetic azimuth. For the paths used in obtaining Fig. 4 the signal frequency f was 14.0 MHz; the take-off angle β was 31.5 deg; the range R was

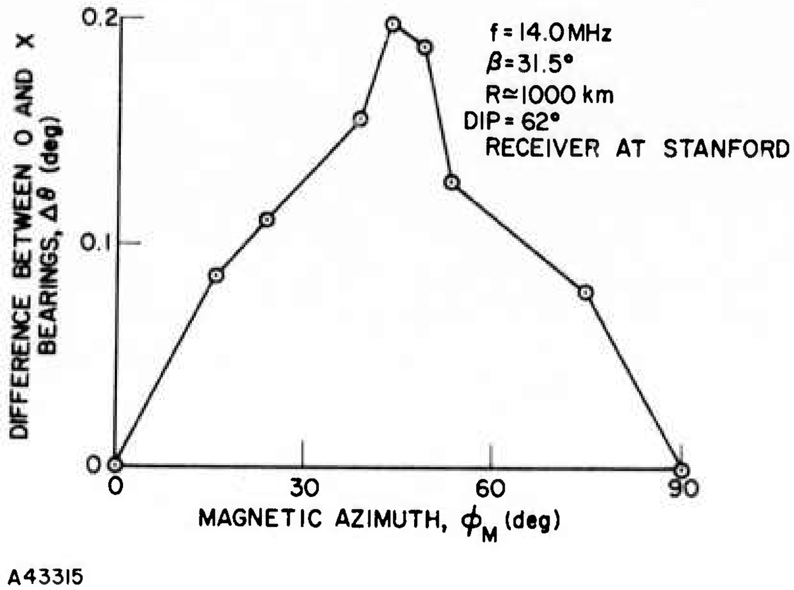

FIG. 4. DIFFERENCE BETWEEN o AND x BEARINGS VS MAGNETIC AZIMUTH. Ray paths chosen near penetration to maximize difference in bearing.

1000 km; and the magnetic dip at the receiver was 62 deg. The maximum difference between the bearings of the two modes is roughly 0.2 deg, occurring near 45 deg magnetic azimuth. The magnitude of $\Delta\theta$ vs ϕ_M was also computed with other values of the parameters; however, because of the small number of cases surveyed in this study, it is valid only to suggest that the effects of net lateral deviation have a broad maximum centered at an angle about midway between the field direction and the perpendicular to the field direction. This behavior occurred in ray-tracings in all four of the azimuthal quadrants. This result also formed a conclusion of the several papers cited in the Introduction.

It is interesting to observe the variation of bearing error with range. Figure 5 shows the result of varying the range for the case where ϕ_M = 45 deg, magnetic dip = 62 deg, and frequency is chosen to

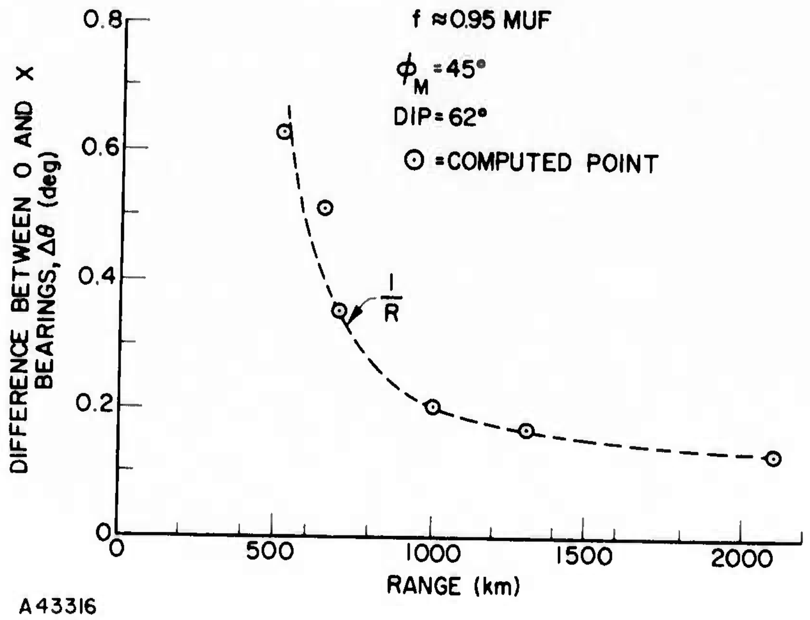

FIG. 5. DIFFERENCE BETWEEN o AND x BEARINGS ($\Delta\theta$) VS RANGE R. Receiver at Stanford.

be roughly 0.95 MUF. Since apparent bearing errors are small, one finds

$$\Delta\theta \simeq \frac{\ell_o + \ell_x}{R} ,$$

where ℓ_o and ℓ_x are, respectively, the ordinary and extraordinary lateral deviations in km, and R is the range in km. A slow variation of the lateral deviation with range gives rise to a variation of $\Delta\theta$ approximately as 1/R over the range increment 500-2000 km, as is shown in Fig. 5 by a comparison of the computed points with the dashed curve. For shorter ranges, of course, this trend must change; however, shorter range paths have not been computed.

It was found that bearing errors tended to be larger for smaller magnetic dip, other conditions being held fixed as closely as possible. A plot of the difference, $\Delta\theta$, between o and x bearings (i.e., bearing error) vs signal frequency for two magnetic dips (62 deg and 0 deg) is shown in Fig. 6. Particularly for F-layer propagation, the effect is larger at 0 deg dip. As far as the interaction of the ray with the magnetic field is concerned, it is not the magnetic azimuth in itself that is important, nor the magnetic dip in itself. The really important parameter is the <u>angle between</u> the field lines and the ray direction. For this reason it is only partially satisfactory to describe the lateral deviation of radio rays in terms of parameters such as magnetic azimuth and magnetic dip which are descriptive of an oblique path as a whole.

In line with the primary interest in this study, it was thought desirable to determine some value for the maximum bearing error resulting from lateral deviation under ionospheric conditions which might be met in

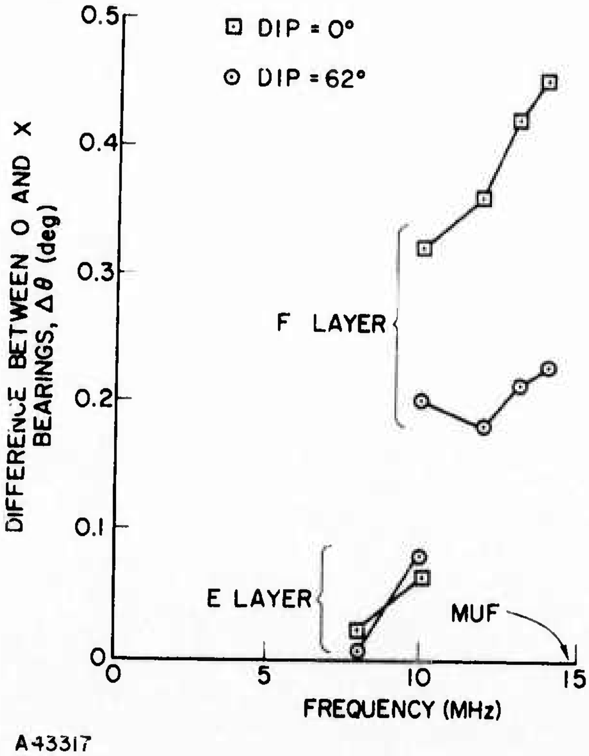

FIG. 6. DIFFERENCE BETWEEN o AND x BEARINGS VS FREQUENCY FOR MAGNETIC DIP ANGLES OF 0° AND 62°. Range = 1000 km, magnetic azimuth = 45 deg.

practice. As indicated by Figs. 4, 5, and 6, the effect is largest (1) for the shorter ranges; (2) near the MUF; (3) at 0 deg magnetic dip; and (4) for propagation at 45 deg from the magnetic meridian. For a range of 1000 km, it is seen in Fig. 6 that the maximum value of $\Delta\theta$ for F-layer propagation in a region of 0 deg magnetic dip is roughly 0.5 deg (corresponding to a situation in which the ordinary and extraordinary modes each have an apparent bearing 0.25 deg away from the true bearing). A plot similar to Fig. 5, except for employing a magnetic dip of 0 deg, would demonstrate that shorter ranges can increase this maximum value several-fold to roughly 2 deg at 500 km; however, the principal interest here was in ranges of 1000 km and more. It is worth repeating,

however, that any estimate of maximum bearing errors due to lateral deviation over oblique paths should include the range as a parameter.

III. ACCURACY AND SIGNIFICANCE OF THE COMPUTATION

Comparison of the predictions made in Section II for lateral-deviation bearing errors with predictions made by previous investigators shows some divergences. Generally speaking, the Finney program gives reasonable values for lateral deviation which appear to be consistent within themselves and are consistent qualitatively with what has been predicted from the analytical considerations of Booker and Millington. However, some means of verification of the accuracy of computations based on the Finney program is clearly necessary. Such a need became apparent in the present investigation when the computations for several paths were performed with transmitter and receiver locations interchanged. For the reversed paths, the angular deviation from the great-circle bearing differed by as much as 10 percent from that for the initial path configurations. This suggests that round-off errors made an appreciable contribution to the computed lateral deviation.

There are several possibilities for checking the computations referred to above. First, Jones (1968) has programmed another version of the Haselgrove equations which is more accurate than the Finney version, although it is still in the developmental stage. Comparative computations performed with both programs would lend insight into the accuracy with which the tedious computation routine itself is carried out. Secondly, it would be extremely satisfying to provide experimental verification of bearing errors caused by lateral deviation. This project would probably involve the use of a large-aperture interferometer with a means for determining fairly detailed information about the ionospheric profile over the path. (Knowledge of ionospheric tilts would be

extremely important.) Finally, a computer-aided analytical study could also provide verification for the computations performed for this report, although this too appears to present a sizable task.

Some years ago the potential bearing errors caused by magnetoionic splitting were considered negligible in most applications; however, with the gathering of knowledge about ionospheric phenomena, the state of the art has progressed to a point for which bearing errors such as those described here may be significant. Of course, the natural field of application of these results would be in direction finding, where lateral deviation may bias the estimate of bearing to the transmitter. If the constraint of making bearing estimates in minimum time is recognized, the bearing variance caused by the numerous sources of error present will almost surely be significantly larger than any bearing bias caused by lateral deviation. (See Gething, 1962, for estimates of variance.)

A further factor in interpreting the bearing errors caused by lateral deviation is that the estimates presented in the present report were computed for the two characteristic modes, ordinary and extraordinary. In general, an antenna (array) will not receive the characteristic polarization. To determine the effects of lateral deviation on the accuracy of azimuthal bearing estimates obtained with a practical receiving array setup, one should employ the estimates for errors for each mode (as in the case presented herein), together with statistical information as to the fading of the ordinary and extraordinary modes. One could then, in principle, obtain a probability distribution of apparent bearing between the two extremes of bearing (ordinary on one side of boresight bearing, and extraordinary on the other).

To summarize the results of this investigation, it may be said that the effects of lateral deviation on azimuthal bearing estimates may be detectable, particularly in the extreme cases cited in this report. For cases of practical interest, this phenomenon leads to errors that are small in relation to other sources of error.

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Stanford Electronics Laboratories Stanford University, Stanford, California	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

LATERAL DEVIATION OF OBLIQUELY PROPAGATED HF RADIO RAYS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

T. W. Washburn

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1968	18	14

8a. CONTRACT OR GRANT NO. Office of Naval Research Contract b. PROJECT NO. Nonr-225(64), NR 088-019 ARPA Order No. 196 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) SEL-68-045 TR No. 137 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Office of Naval Research, Field Projects Branch, Washington, D. C., 20360.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research Advanced Research Projects Agency

13. ABSTRACT

As is well known, magnetoionic splitting of obliquely propagated HF radio waves may result in deviation of such waves from the great-circle plane between transmitter and receiver. A computer raytracing routine has been employed at Stanford to investigate the properties and maximum extent of this phenomenon under realistic ionospheric conditions. It is concluded that for a 1000 km path the difference in azimuthal bearing between the ordinary and extraordinary modes could reach a maximum of 0.5 deg, corresponding to an 0.25 deg variation of either mode from the true bearing. However, in most practical bearing estimation problems, the difference is an order of magnitude smaller than this maximum, and thus is truly small in comparison with other sources of error.

DD FORM 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
IONOSPHERIC PROPAGATION RAYTRACING LATERAL DEVIATION DIRECTION FINDING, AS AZIMUTHAL BEARING ERROR						